ULTRA WIDEBAND SCRAMBLER FOR REDUCING POWER SPECTRAL DENSITY

FIELD OF THE INVENTION

[0001] The present invention relates to Ultra Wideband transmission technology and, more particularly, to Ultra Wideband signal scrambling methods and apparatus for reducing the power spectral density due to discrete frequency components of Ultra Wideband signals.

BACKGROUND OF THE INVENTION

[0002] Ultra Wideband (UWB) technology uses base-band pulses of very short duration to spread the energy of transmitted signals very thinly from near zero to several GHz. UWB technology is presently in use in military applications and techniques for generating UWB signals are well known. Commercial applications will soon become possible due to a recent decision announced by the Federal Communications Commission (FCC) that permits the marketing and operation of consumer products incorporating UWB technology.

[0003] The key motivation for the FCC's decision to allow commercial applications is that no new communication spectrum is required for UWB transmissions because, when they are properly configured, UWB signals can coexist with other application signals in the same spectrum with negligible mutual interference. In order to ensure negligible mutual interference, however, the FCC has specified emission limits for the UWB applications. For example, a basic FCC requirement is that UWB systems do not generate signals that interfere with other narrowband communication systems.

[0004] The emission profile of a UWB signal can be determined by examining its power spectral density (PSD). The PSD for ideal synchronous data pulse streams based upon stochastic theory is well known. Characterization of the PSD of a "Time-Hopping Spread Spectrum" signaling scheme in the presence of random timing jitter using a stochastic approach is disclosed in an article by Moe et al. entitled "On the Power Spectral Density of Digital Pulse Streams Generated by M-ary Cyclostationary Sequences in the Presence of Stationary Timing Jitter." See IEEE Tran. on Comm., Vol. 46, no. 9, pp. 1135-1145, Sept. 1998. According to this article, the power spectra of UWB signals consists of continuous and discrete components. Generally speaking, discrete components contribute more to the PSD than continuous components. Thus, discrete components cause more interference to narrowband wireless systems than continuous components.

[0005] Data whitening can reduce the presence of discrete components and, thereby, reduce the PSD of UWB signals. In traditional communication systems, scramblers are commonly used for data whitening, e.g., for timing recovery and equalization. Their performance in suppressing PSD, however, is not sufficient for use with UWB signals. For example, when a block of data is repeated, strong line spectra may be generated even though data inside the block is scrambled. This is the case for IEEE 802.15.3a, which is a standard being developed by the Institute of Electrical and Electronic Engineers (IEEE). Traditional scramblers are not sufficient in suppressing PSD in IEEE 802.5.3a because of an associated high pulse repetition frequency (PRF), i.e., about 100 Mbps to 500 Mbps, and their time division multiple access (TDMA) frame structure.

[0006] Accordingly, improved scramblers for reducing the PSD of UWB signals are needed. The present invention fulfills this need among others.

SUMMARY OF THE INVENTION

[0007] The present invention is embodied in apparatus and a method for scrambling UWB data by shifting a first bit string a first number of bits, shifting a second bit string a second number of bits, combining the first and second shifted bit strings and generating scrambler control bits from the combined first and second shifted bit strings. At least a portion of the UWB data is scrambled responsive to the generated scrambler control bits.

[0008] According to another aspect of the invention, UWB data is scrambled by scrambling the payload data using a pseudo random sequence which is initialized using a seed selected from a seed set having substantially uncorrelated seed values. Non-payload portions of the scrambled data are then selectively inverted.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention is best understood from the following detailed description when read in connection with the accompanying drawings, with like elements having the same reference numerals. Included in the drawings are the following figures:

FIG. 1A is a graph depicting frequency versus power spectral density (PSD) for one pulse;

FIGs. 1B, 1C, and 1D are graphs depicting frequency versus PSD for random sequence probabilities of 0.25, 0.5, and 1, respectively;

FIG. 2A depicts the general structure of a TDMA system;

FIG. 2B is a graph depicting data inside a frame for consecutive frames in a TDMA system;

FIG. 3A depicts the PSD of frames with multiple original data pulses;

FIG. 3B depicts the PSD of frames with multiple data processed pulses in accordance with the prior art;

FIG. 4A is a block diagram of a two layer linear feedback shift register (LFSR) for use in a scrambler in accordance with one embodiment of the present invention;

Fig 4B is a block diagram of a random frame reversion circuit according to an exemplary embodiment of the present invention.

FIGs. 5A and 5B depict a PSD comparison of initial scrambler settings for four seeds in accordance with the prior art and for a two-layer LFSR in accordance with the present invention, when used with data having a 1024-byte frame size;

FIGs. 5C and 5D depict a PSD comparison of initial scrambler settings for four seeds in accordance with the prior art and for a two-layer LFSR in accordance with the present invention, when used with data having a 256-byte frame size;

FIGs. 5E and 5F depict a PSD comparison of initial scrambler settings for four seeds in accordance with the prior art and for a two-layer LFSR in accordance with the present invention when used with data having a 64-byte frame size;

FIGs. 6A and 6B depict a PSD comparison of scramblers for a 15 bit two-layer LFSR (LFSR-15) when used with four correlated seeds and four uncorrelated seeds, in accordance with the present invention;

FIGs. 7A and 7B depict a PSD comparison of a two-layer LFSR-15 used with four uncorrelated seeds, without random frame reversion (RFR) and with RFR, respectively, in accordance with the present invention;

FIGs. 8A and 8B depict a PSD comparison of a prior art scrambler and a two-layer LFSR-15 used with eight and sixteen uncorrelated seeds respectively and without RFR in accordance with the present invention;

FIGs. 8C and 8D depict a PSD comparison of a prior art scrambler and a two-layer LFSR-15 used with eight and sixteen uncorrelated seeds respectively and with RFR in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0010] In order to understand the present invention, an analysis of the PSD of a clocked random sequence is useful. Assume that a digitally controlled signal produces

random transmissions at multiples of the basic clock period *Tc*. This signaling technique is modeled as shown in equation 1:

$$s(t) = \sum_{n=-\infty}^{\infty} a_n w(t - nT_c) \qquad (1)$$

where $\{a_n\}$ is an unbalanced binary independent identically distributed (i.i.d.) random sequence and w is a time domain pulse that determines pulse shape and transmission power. It is assumed that $\{a_n\}$ is stationary with a probability function as shown in equation 2:

$$\Pr\{a_n\} = \begin{cases} p, & a_n = 1 \\ 1-p, & a_n = -1 \end{cases} \qquad (2)$$

[0011] It is known by those of skill in the art that the continuous component $S^c(f)$ and the discrete component $S^d(f)$ of a UWB signal can be modeled as shown in equations 3a and 3b, respectively:

$$S^c(f) = \frac{1}{Tc}|W(f)|^2\left\{1-(2p-1)^2\right\} \qquad (3a)$$

$$S^d(f) = \frac{(2p-1)^2}{Tc^2}\sum_{l=-\infty}^{\infty}\left|W\left(\frac{1}{Tc}\right)\right|^2 \delta_D\left(f-\frac{1}{Tc}\right) \qquad (3b)$$

[0012] These equations indicate that the PSD is determined by three parameters, i.e.,

- $W(f)$ – pulse shape and transmission power;
- Tc – clock period or pulse rate; and
- p – distribution of a_n.

From the above determinations, the following conditions are derived:

- $S^c(f, 0) = 0$ and $S^d(f, 0) = max(S^d(f))$ when $p=0$ and
- $S^c(f, 1) = 0$ and $S^d(f, 1) = max(S^d(f))$ when $p=1$.

  (In these cases, $S^d(f)$ reaches a maximum and all energy goes to the discrete component no matter what waveform is used for pulses.)

- $S^c(f, 0.5) = \max(S^c(f))$ and $S^d(f, 0.5) = 0$ when $p=0.5$.

  (In this case, $S^c(f)$ reaches a maximum and all energy goes to the continuous component no matter what waveform is used.)

Thus, if the total PSD is kept constant, the distribution of the random sequence will determine the distribution of the PSD between the continuous and discrete components.

[0013] FIG. 1A depicts the power spectrum of one pulse and FIGs. 1B-1D depict the PSDs of clocked random sequences with different probabilities of distribution *p*. In particular, FIG. 1B gives the PSD of $p=0.25$, FIG. 1C of $p=0.5$, and FIG. 1D of $p=1.0$. These figures illustrate that changing *p* will, in turn, change the distribution of the PSD between continuous and discrete component and that the discrete component exhibits higher PSD than the continuous component. It is clear that when $p=1.0$, only line spectra exist; when $p=0.5$, only the continuous component exists; and when p=0.25, both continuous and discrete components exist. These figures confirm the conclusion derived from equations 3a and 3b.

[0014] The PSD of a time division multiple access (TDMA) system is now described. The IEEE 802.15.3a standard employs an IEEE 802.15.3 media access control (MAC) layer, which is a TDMA system. Line spectra appear if pulses in a TDMA frames are not evenly distributed between 1 and −1. FIGs. 2A and 2B illustrate the problem schematically. FIG. 2A illustrates the general structure of a TDMA system in which the start of each frame is separated by Tc. FIG. 2B illustrates that bits in a frame form a repeating pulse train. As shown in FIG. 1C, only when pulses are randomly and evenly distributed in the Y direction (i.e., between 1 and -1) are line frequencies suppressed. The repeating pulse train generates line spectra even though data inside the block is scrambled. Therefore, traditional scramblers are insufficient in suppressing PSD since data on the Y direction is not evenly distributed.

[0015] FIGs. 3A and 3B depict PSDs of a TDMA system in which a frame consists of eight pulses. These figures illustrate that if pulses are not evenly distributed between 1 and −1 in the Y direction, line spectra appear although pulses are randomly distributed inside the frames. FIG. 3A depicts the PSD of original data and FIG. 3B depicts the PSD of the data processed by prior art schemes. It is assumed that the data changes randomly and independently. The data, however, is not necessarily distributed evenly in the Y direction, thus, *p* is not always equal to 0.5. It can be seen that the data generates both continuous and discrete spectra because *p* is not always 0.5.

[0016] Presently, major system proposals to IEEE 802.15.3a employ an IEEE 802.15.3 MAC and a scrambler with a 15-bit Linear Feedback Shift Register (LFSR) to generate a pseudo random binary sequence (PRBS) for the scrambler. In IEEE 802.15.3, the scrambler is applied to payload data of a data sequence including

payload and non-payload data and is also applied to some upper layer data. At the beginning of each frame, the scrambler is loaded with predefined values, which are referred to herein as initial settings. Four seeds indexed with a two bit identifier (b_1, b_0) are defined for selection as the initial setting, which is illustrated in Table 1.

Table 1.

Seed identifier (b_1, b_0)	**Seed value (x_{14} ... x_0)**
0,0	0011 1111 1111 111
0,1	0111 1111 1111 111
1,0	1011 1111 1111 111
1,1	1111 1111 1111 111

As depicted in Table 1, the seed values are highly correlated (i.e., only the first two bits of each seed value are unique) and, thus, line spectra may result from a lack of adequate randomness. For the next generation of UWB, which provides 4Gbps data rate, the problem will become more obvious.

[0017] Scrambler architectures and schemes in accordance with the present invention for PSD suppression in IEEE 802.15.3a systems, for example, are now depicted. In an exemplary embodiment, a two-layer LFSR architecture is proposed for payload data in order to increase randomness of the initial setting of the scrambler, thus increasing randomness in the Y direction.

[0018] An exemplary two-layer LFSR is depicted in FIG. 4. The exemplary circuit 422 includes two shift registers 410 and 412, a plurality of exclusive OR (XOR) circuits 414a through 414n, a control shift register 416 and an XOR circuit 418. In an exemplary embodiment, with reference to FIG. 4, the two-layer LFSR operates as follows:

1. At the beginning of each frame, right shift sign_ctl_orig1 412 for *n1* bits and sign_ctl_orig2 410 for *n2* bits, where n1 and n2 are each predetermined values between 1 and the maximum number of shifts, e.g., 14 for the 15 bit shift register depicted in FIG. 4;

2. Exclusive OR (XOR) the shifted original numbers, sign_ctl_orig = sign_ctl_orig1 ⊕ sign_ctl_orig2 in the XOR circuits 414A through 414N;

3. Load sign_ctl_orig to sign_ctl_reg 416;

4. Use sign_ctl_reg to generate required sign control bits for scrambling the payload data;

5. Go to step 1 for next frame.

[0019] Simulations are now described for different initial settings of the scrambler. In these simulations, the payload data are all "1"s and there is no non-payload data. The pulse rate is 4 Gbps and resolution is 100kHz. Frame sizes of 1024 Bytes, 256 Bytes and 64 Bytes are used. The 1024 Bytes frame size is requested for evaluation in IEEE 802.15.3a; the 64 Byte frame size is the minimum frame size in the specification. The simulation results are shown in FIGs. 5A and 5B for frame size of 1024 Bytes, 5C and 5D for frame size of 256 Bytes and 5E and 5F for frame size of 64 Bytes. FIG. 5A, 5C and 5E depict an LFSR-15 with the four seeds shown in Table 1, and FIG. 5B, 5D and 5F depict a two-layer LFSR with 15 shift bits per layer (i.e., LFSR-15). The shift bits for the two layer LSFR-15 are generated using a 15-bit polynomial generator that produces a pseudo random binary sequence (PRBS) and result show that this two-layer LFSR-15 reduces the PSD by about 13dB, 26dB and 34dB respectively.

[0020] Alternatively, a random sequence may be generating from collected physical noise sequences, for example, Shot noise, Johnson noise, 1/F noise, oceanic ambient noise, and photon noise. Other noise sequences may also be used. The noise sequences may be amplified and A/D converted. A bit stream from this digitized sequence may then be used as the random sequence. To synchronize the receiver and transmitter, it may be desirable to send the random sequence as a preamble to the message that is scrambled with the sequence.

[0021] The above schemes provide improvements in suppression of line spectra. For this implementation it is required that the scramblers in the transmitter and the receivers are synchronized.

[0022] It is noted that the scrambler seed selection mechanism in IEEE 802.15.3 as shown in Table 1 results in seeds that have high correlation. In this implementation, the LFSR-15 has (2^{15}-1) states. The seeds may be defined as Seed4 = state(n), Seed2 = state(n+1); and Seed1 = state(n+2). It is noted that there may be too much overlap in states among the three seeds. If, for example, one frame of 1024 bytes uses 2^{13} states, four frames use states <= 2^{13}(Seed3)+ (2^{13} +2)= 2^{14}+2<(2^{15}-1). Thus, this scrambler may not provide sufficient randomness for all applications.

[0023] This observation suggests that other sets of seeds that are independent from each other would provide better randomness in scrambler settings than are provided by the prior art.

[0024] An exemplary seed set having seeds that are substantially uncorrelated are depicted in Table 2.

Table 2.

Seed identifier (b_1, b_0)	**Seed value (x_{14} ... x_0)**
0,0	1111 1111 1111 111
0,1	0111 0000 1111 111
1,0	0111 1111 0000 000
1,1	0111 1000 0000 111

The four new seeds may be described as follows:

Seed1 = state(n)

Seed2 = state(mod(n+1*2^{15-2}, 2^{15}))

Seed3 = state(mod(n+2*2^{15-2}, 2^{15}))

Seed4 = state(mod(n+3*2^{15-2}, 2^{15}))

Using these seeds, there is no state overlap among the four seeds. One frame of 1K bytes has 2^{13} states and four frames use states = $4*2^{13}=2^{15} > 2^{14}+2$. This analysis shows that the use of the four uncorrelated seeds increases the randomness of the scrambling.

[0025] Simulations are now described. Payload data are all "1"s to the scrambler and there is no non-payload data. The pulse rate is 4 Gbps and resolution is 100kHz. Frame size of 256 Bytes is used. The simulation results are shown in FIGs. 6A and 6B in which FIG. 6A depicts an LFSR-15 with four correlated seeds, shown in Table 1, and FIG. 6B depicts an LFSR-15 with four uncorrelated seeds, shown in Table 2. These simulation results show that the uncorrelated seeds reduce the PSD by about 10dB.

[0026] As illustrated in FIG 6B, spectra lines, although improved, still exist. These lines are associated with the relatively small number of seeds. To further reduce spectra lines, random frame reversion is proposed. Another reason for introducing random frame reversion is explained in the next paragraph.

[0027] Since IEEE 802.15.3a utilizes IEEE 802.15.3 MAC, the maximal frame length is 2KByte. Assuming the data rate of the UWB is 4Gbps, the minimal frame rate would be:

4G/(2K*8) = 256K

$T_f = 4*10^{-6}$ (4)

Because $T_f<<1$, non-payload data (e.g., synchronization words) may generate strong spectra lines if viewed using finer resolution. Table 2 lists some values that the non-payload data contributes to the PSD with assumption of $T_f=10^{-3}$, where p_{st} is the percentage of non-payload data in a frame. This table indicates that although non-payload data constitutes a small portion of a frame, their contribution to the PSD cannot be neglected due to the high pulse repetition frequency (PRF) of the frames. If a smaller frame length is used in harsh environments to reduce frame error rate, the same percentage of non-payload data generate stronger spectral lines and more PSD than those listed in Table 3.

Table 3

p_{s+}	**ΔPSD (dB)**
0.1%	3.01
0.5%	7.78
1%	10.41
5%	17.07
10%	20.04

[0028] To further reduce the PSD of new scrambler and reduce the PSD generated by non-payload data, the following scheme of random frame reversion (RFR) is proposed. A framed data stream can be expressed as shown in equation 5:

$$s(t)=\sum_{l=-\infty}^{\infty}\sum_{k=1}^{K}a_{l,k}w(t-lT_f-kT_p) \qquad (5)$$

where l and k are index values of frames and pulses in frames, respectively.

[0029] RFR is able to reduce spectra lines generated by non-payload data, which is not scrambled. In an exemplary embodiment, RFR is implemented as follows:

- A random sequence $\{b_n\}$ is generated with the following evenly distributed function:

$$\Pr\{b_n\}=\begin{cases}0.5, & b_n=1\\ 0.5, & b_n=-1\end{cases}$$

- The following operation is then applied to the data sequence to produce a new sequence:

$$c_{l,k} = \begin{cases} a_{l,k}, & b_l = 1 \\ -a_{l,k}, & b_l = -1 \end{cases}$$

- $\{c_{l,k}\}$ is transmitted as the new data sequence.

[0030] An exemplary circuit for performing random frame reversion is shown in Fig. 4B. In this Figure, payload data is scrambled in a circuit 424 responsive to a scramble sequence provided by a scramble generator, for example the scramble generator 422 described above. The non-payload data is inserted into the frame by a circuit 426 after the payload data has been scrambled and, so, is not scrambled. The output signal of circuit 426 is applied to a selective inverter 428 which is responsive to a random bit generator 430. The inverter 428 either passes the data of a frame as it receives it or inverts the data of the frame responsive to the signal from the random generator 430. Using this circuit, the entire frame may be selectively inverted responsive to random bits provided by the random number generator 430 or it may be passed without being inverted.

[0031] Simulation results are shown in FIG. 7A and 7B . The pulse rate is 4 Gbps and resolution is 100kHz. A frame size of 256 Bytes is used. Payload data are all "1"s to the scrambler. FIG. 7A depicts the PSD of data processed by the new seed LFSR-15 without RFR and FIG. 7B depicts the PSD of data processed by the new seed LFSR-15 with RFR. The results showed that RFR reduces PSD by about 10dB.

[0032] In an alternative exemplary embodiment, the following scheme is proposed:

1. Different seed values for seed selection (i.e., more random);
2. Selective random frame reversion (RFR) at least for non-payload data.

[0033] In Table 2, there are four seed values and each seed value includes 15 bits. The seed values are substantially uncorrelated and, therefore, pseudo random sequences generated using these seed values are substantially uncorrelated. The seed set shown in Table 2 is for illustration only and seed sets with seeds having different seed values, more or less seeds, and more or less bits per seed may be employed. Those of skill in the art will understand how to generate suitable uncorrelated seed values for use in a seed set from the description herein. A simulation with seed sets having different numbers of seed are generated using the same configuration as above.

The simulation results are illustrated in FIGs. 8A, 8B, 8C and 8D for random seed sets of 8- and 16-seeds for comparison. 8A and 8B depict respective sets of 8- and 16-seeds without RFR and FIGs 8C and 8D depict respective sets of 8- and 16-seeds with RFR. The seeds for the simulation depicted in FIGs. 8A-8D are generated using a MATLAB rand() function.

[0034] The simulations show that:

- The new scheme reduces the PSD of UWB signals significantly;
- Without using RFR, 16 seed sets are about 5 dB better than 8 seed sets, and 8 seed sets are about 1 dB better than 4 seed sets; and
- Using RFR, 16 seed sets are about 1 dB better than 8 seed sets, and 8 seed sets are about 3 dB better than 4 seed sets. The three sets of seeds show very similar performance.

[0035] Accordingly, it is concluded that a simple and effective design of a scrambler for line spectra control may be as follows:

1. Use seed selection from a 4-seed set (or greater) with low seed correlation (i.e., random);
2. Use selective RFR for non-payload data.

[0036] The above description provides an analysis of the effect of scrambling on the PSD of UWB signals in IEEE 802.15.3a systems and proposes new whitening schemes to contain the PSD. Simulations show that the current scrambler proposed in IEEE 802.15.3a is not sufficient and the new whitening schemes can improve performance in suppressing the PSD. The new scheme is easy to implement and does not require MAC layer changes. The scheme can be used in the development of an IEEE 802.15.3a scrambler.

[0037] Although the components of the present invention have been described in terms of specific components, it is contemplated that one or more of the components may be implemented in software running on a general purpose computer. In this embodiment, one or more of the functions of the various components may be implemented in software that controls the general purpose computer. This software may be embodied in a computer readable carrier, for example, a magnetic or optical disk, a memory-card or an audio frequency, radio-frequency or optical carrier wave.

[0038] In addition, although the invention is illustrated and described herein with reference to specific embodiments, the invention is not intended to be limited to the details shown. Rather, various modifications may be made in the details within the

scope and range of equivalents of the claims and without departing from the invention. For example, although the present invention has been described with reference to reducing the PSD of UWB signals under IEEE 802.15.3a, it is contemplated that the present invention may be used to reduce PSD in other communication systems and standards.